



National Aeronautics and
Space Administration
Jet Propulsion Laboratory
California Institute of Technology



Michelson Science Center

Probing the Inner Rim of Pre-Planetary Disks with IOTA Closure Phases

Rafael Millan-Gabet

Collaborators:

John Monnier, U. Michigan

Jean-Philippe Berger, LAOG, France

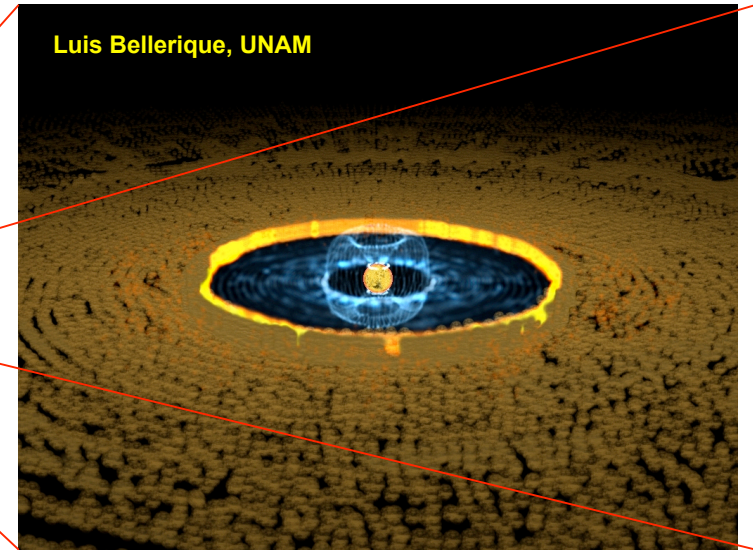
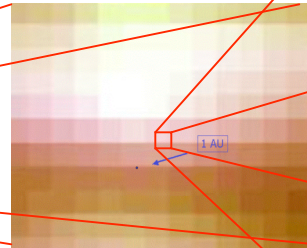
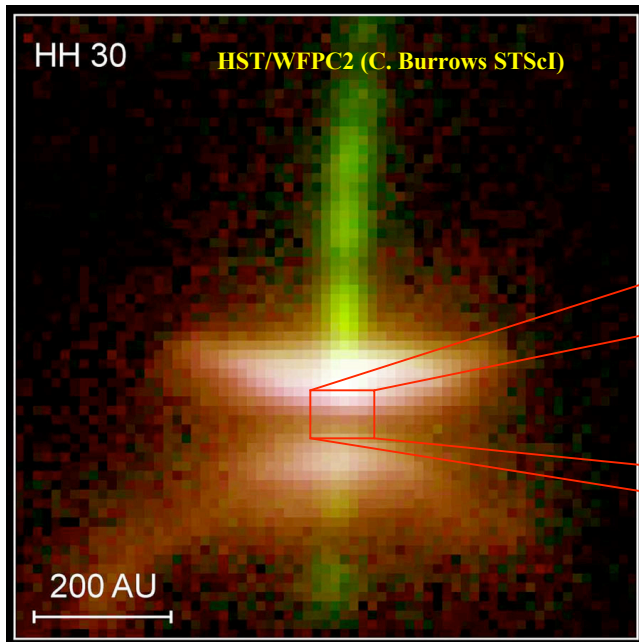
Wes Traub, JPL

Pete Schloerb, U. Massachusetts

CS14 - TPF/Darwin Workshop November 8-11 2006

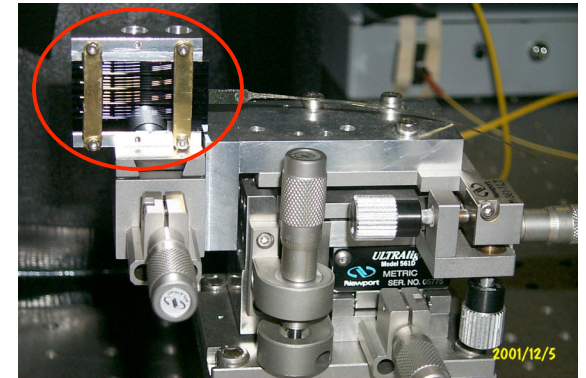


Motivation for IR Interferometry of YSOs



- Interferometer angular resolution $\sim \lambda/B = 11$ mas for $B=38$ m, $2.2\mu\text{m}$.
⇒ Sub-AU to few-AU for $d=100$ - 1000 pc.
⇒ Directly probe the inner-most disk regions.
 - Star and disk formation, accretion theories.
 - Initial conditions for planet formation.

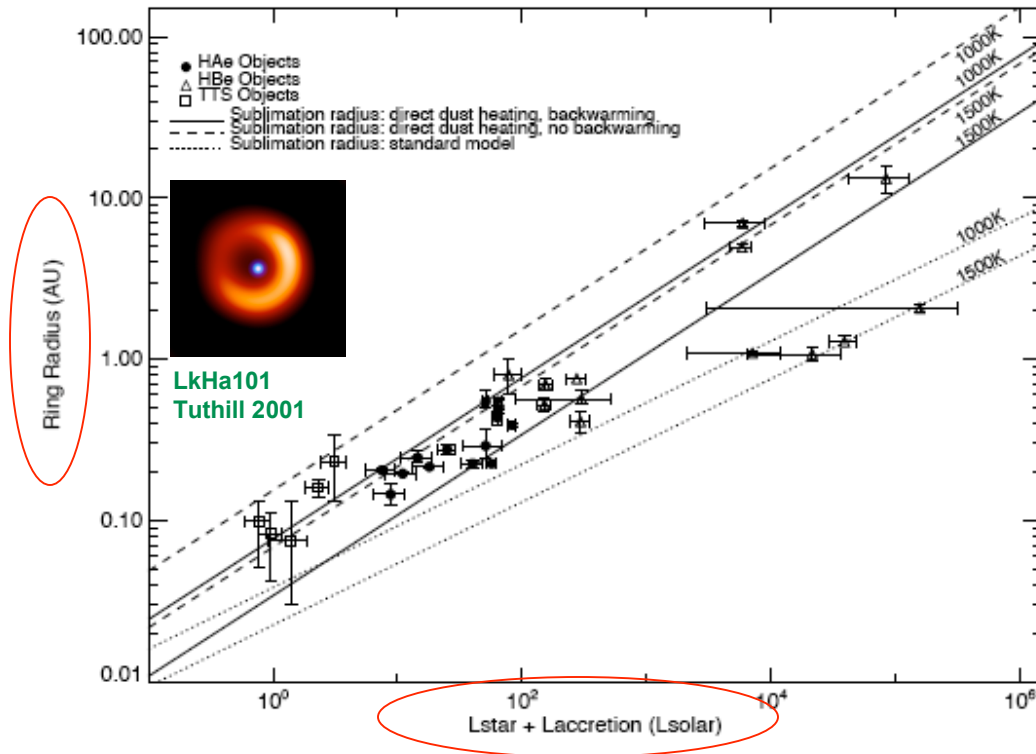
The Infrared Optical Telescope Array Mt Hopkins, AZ 1992 - 2006



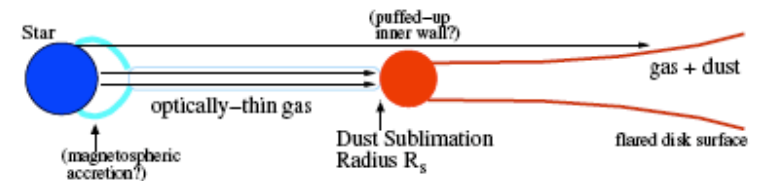
- SAO, UMass + Meudon, Grenoble and other collaborators.
- 3 Telescopes, $D=50\text{cm}$.
- Relocatable along 2 tracks.
- Baseline length range = 5 - 38 m.
- First 3-telescope fringes in 2002.
- 3 Simultaneous baselines, 3 fringe amplitudes, one closure phase.
- Uses miniature integrated optics beam combiner (very stable).
- The YSO Survey:
 - 14 young stellar objects, mostly Herbig Ae/Be type.
 - H band ($1.65\mu\text{m}$) mostly.



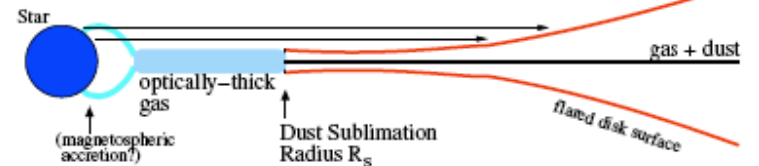
Context: Previous Results with 2 Telescopes



Direct heating of inner dust disk



"Standard" Disk Model – oblique disk heating



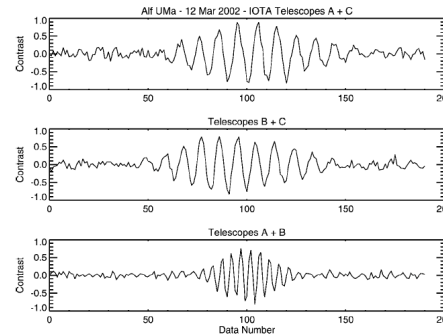
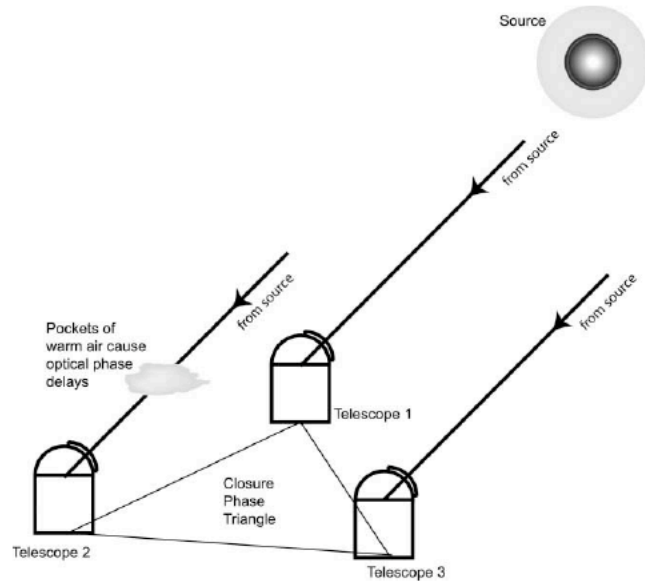
Reviewed in Millan-Gabet et al. Protostars and Planets V

Characteristic near-infrared sizes of many YSOs measured by IOTA, PTI, and KI played an crucial role in establishing the new YSO inner-disk paradigm: the “puffed-up” inner rim (Natta et al. 2001, Dullemond et al. 2001).

Now taken the next step in these studies by probing **higher-order morphology** of the inner disk ...



The Closure Phase



Observed	Intrinsic	Atmosphere
$\Phi(1-2)$	$= \Phi_o(1-2)$	$+ [\phi(2)-\phi(1)]$
$\Phi(2-3)$	$= \Phi_o(2-3)$	$+ [\phi(3)-\phi(2)]$
$\Phi(3-1)$	$= \Phi_o(3-1)$	$+ [\phi(1)-\phi(3)]$

Closure Phase (1-2-3) $= \Phi_o(1-2) + \Phi_o(2-3) + \Phi_o(3-1)$

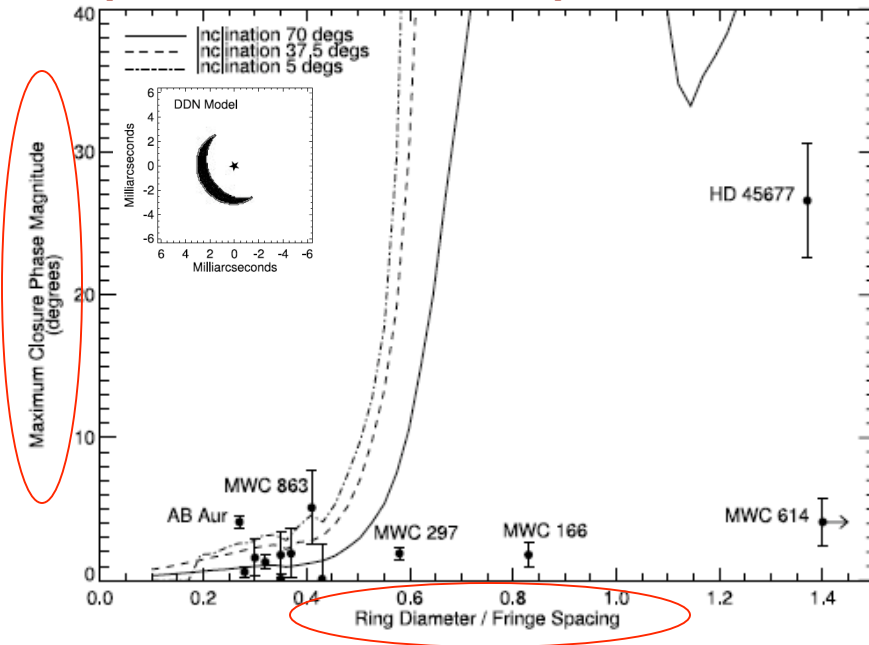
- One fringe, one baseline, measures one Fourier component of the object brightness.
- The atmosphere scrambles the fringe **phases**.
- The **closure phase** is **independent** of these atmospheric terms.
- $CP = 0$ (or 180deg) for point-symmetric images.
- $CP \neq 0$ indicates **skewed emission**, deviations from point-symmetry (**expected** for inner disk emission in a flared, inclined, disk).
- ✓ A key probe for YSO studies, since model-independent image reconstruction is not possible given limited uv coverage of current facilities.
- Note: to obtain a CP signal, emission must be *resolved*.



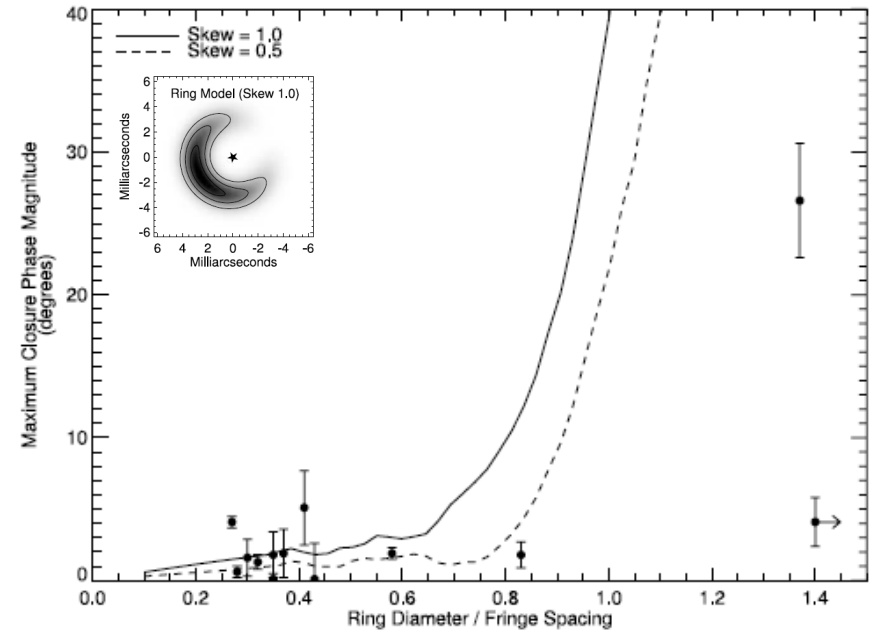
Results I: The Sample as a Whole

Monnier et al. 2006, ApJ.

Vertical inner rim
(as in Dullemond et al. 2001)



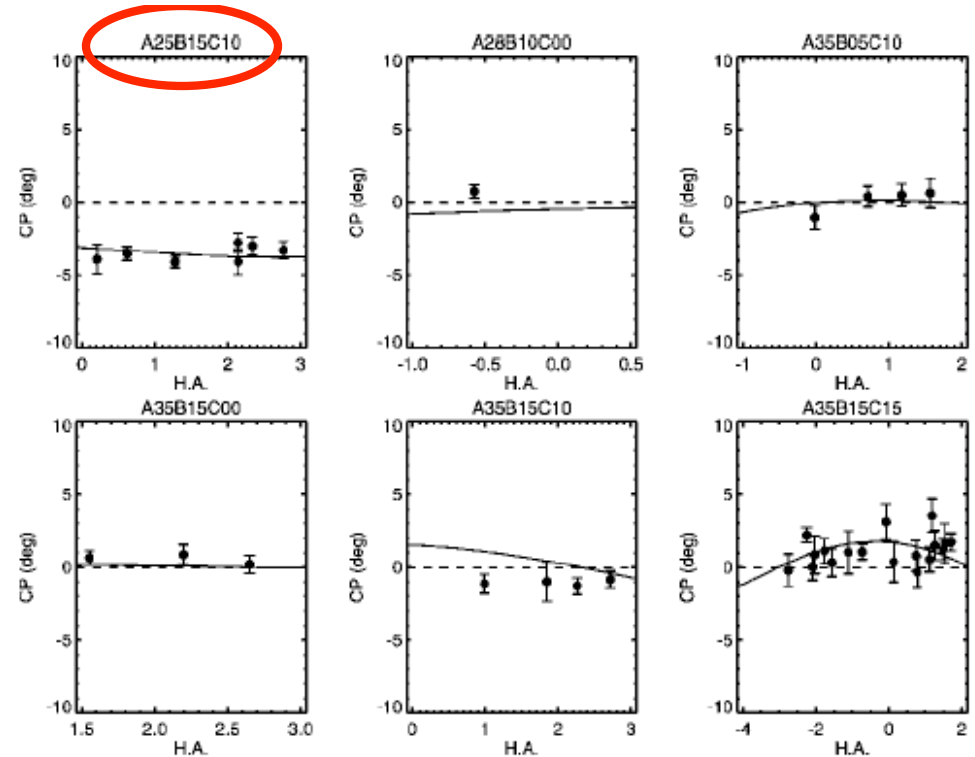
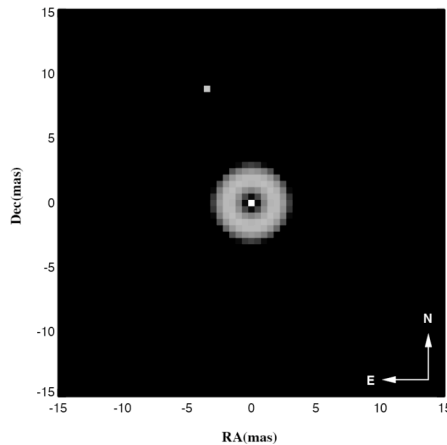
Rounded inner rim



- ✓ The measured CPs are generally non-zero but small.
- ✓ For about 1/2 of the sample, reflects limited IOTA resolution.
- ✓ Low CPs measured rule out the original inner rim models possessing a perfectly vertical inner dust wall.
- ✓ Our measurements favor smoother inner rim physical structure:
 - ✓ Expected from pressure-dependent dust sublimation temperature (Isella 2005).
 - ✓ Expected (even more) from dust settling effects (Tannirkulam 2006).

Results II: The Case of AB Aur

Millan-Gabet et al. 2006, ApJ.

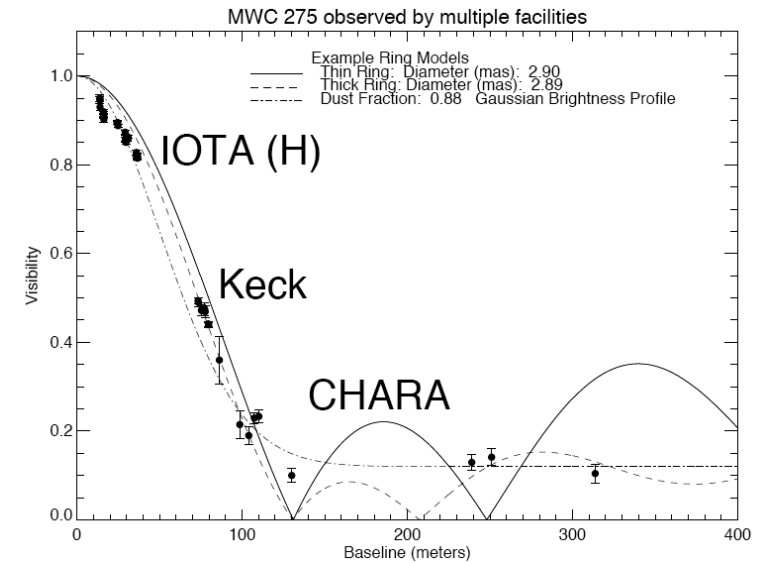


- ✓ On most baseline triangles $CP \sim 0$ deg, confirming high degree of point-symmetry on sub-AU scales.
- ✓ A clear CP signal -3 to -4 deg detected only in a triangle of relatively **short baselines**, indicating a high degree of skewness at **larger spatial scales**.
- ✓ Used offset Gaussian spot to characterize the extra asymmetry needed. Typical solutions have **compact spot** (10-30mas) at 1-4AU with 2-8% flux.
- × H-band scattering in disk halo (would not be compact).
- × Also not opacity / obscuration effects (low disk inclination).
- ✓ We favor compact thermal emission
 - Local disk inhomogeneity unlikely given dynamical t-scales vs. age of the system.
 - Gravitational instability in non-steady disk (implications for planet formation).
 - Companion, but would imply disk survival in spite of close separation.
 - Exciting possibility: proto-planetary object forming in the disk?
 - Testable hypothesis (variability 1-5yr orbital motion; high res. imaging single telescopes).



Future Prospects

- To efficiently probe inner-disk morphology for most YSO objects, need CP measurements with **100m baselines** (e.g. MIRC/CHARA, AMBER/VLTI, IONIC3/PTI?).
- **Physical modeling of individual objects**, testing detailed inner rim dust effects, and incorporating constraints from e.g. CO maps or scattered light images.
- Given sufficient uv coverage, direct image reconstruction of inner disk, for **model independent** view of the physical conditions in these pre-planetary environments.



CHARA/MIRC record-breaking closure phase precision demonstrated

